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Overview of Seismic Noise and its Relevance to Personnel Detection

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Prepared for U.S. Army Corps of Engineers

Abstract: Seismic noise refers to the ambient ground motion within which signals of interest are to be detected. Four categories of seismic noise identified by source—road (vehicle), train, wind, and ocean microseisms—are reviewed. Examples are given of the variation in seismic noise by geographic location and by season and time of day, and of a technique to characterize seismic site effects from local seismic noise. Noise impact on seismic detection of personnel is discussed, and ground motion induced by a walking person is compared with noise at a rural site when cultural activity is minimal and when a moving vehicle is present.

Contents

Figures and Tables

Figures

Tables

Preface

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1 Introduction

This report presents an overview of seismic noise, which is the ambient ground motion within which signals of interest are to be detected. Equivalent terms are seismic clutter and (seismic) background noise. Seismic noise generally is a mix of components attributable to natural and cultural sources, with the type and proportion of each dependent on location and often time of day. Wind-induced motion of surface objects is a prevalent natural cause of seismic noise; operating machinery (including moving vehicles) is the primary cultural cause. The information compiled will assist in assessing the sources of seismic noise at a location and in anticipating its frequency content and variation.

2 Review of Seismic Noise

General Characteristics

Peterson (1993) generated noise power spectral density plots over frequencies up to 10 Hz for each of 75 stations worldwide. From the combined curves, he defined two parameters—a new low noise model (NLNM) and a new high noise model (NHNM)—which replaced earlier low and high noise models, respectively (Peterson 1980). Neither the NLNM nor the NHNM was ever likely to represent the actual noise spectrum at a specific site, the former because it is a composite of curves that individually are influenced by instrumentation, geology, and geography, the latter because it is an average over the network. McNamara and Buland (2004) pointed out that NLNM has become less representative over time for stations within the network that have been encroached upon by urban sprawl and now experience stronger cultural noise. As standards in the seismology community, however, NLNM and NHNM are useful in the intercomparison of noise fields from different sites (Fig. 1).

Variability in noise from site to site was also discussed by Douze (1967), for frequencies of ~0.1 to 3 Hz, and Kanasewich (1990). Kanasewich assessed published noise spectra and concluded that, under low wind conditions (less than ~3 m/s), seismic noise decreases rapidly between 0.1 and 1 Hz. He identified a particle velocity of 10^{-5} cm/s/Hz peak to peak as a good average for many continental sites but qualified that statement with the observation that areas with noise ten times greater are numerous and that wind speeds higher than ~8 m/s can increase noise by at least a factor of five. Kanasewich cited, for frequencies of 10 to 100 Hz, a particle velocity of ~10^{-6} cm/s/Hz as representative of low noise conditions, but he noted that site differences can cause variations in particle velocity in the range 10^{-5} cm/s/Hz to 10^{-7} cm/s/Hz.

Bard et al. (2003) analyzed published noise studies as part of the SESAME (*S*ite *E*ffects Assessment using *Am*bient *E*xcitations) program and made the following differentiations:

- At frequencies below 0.5 Hz, noise sources are natural (oceanic and large-scale meteorological conditions) and noise is termed "microseisms."

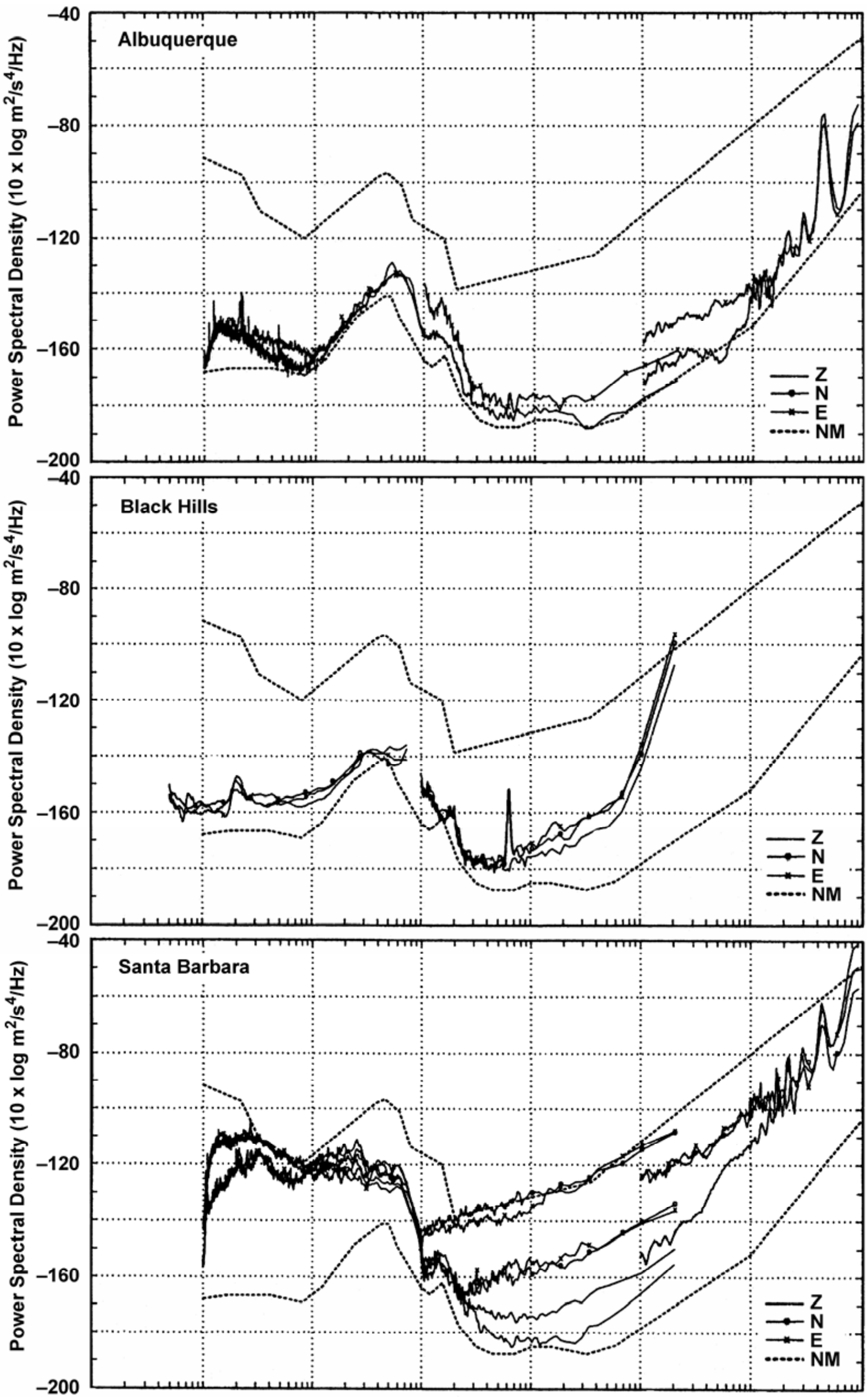

Figure 1. Noise spectra from three stations represented in the noise models developed by Peterson (1993). In each plot, the upper dashed line is the NHNM; the lower dashed line is the NLNM.

- At ~1 Hz, sources are wind effects and local meteorological conditions.
- At frequencies above 1 Hz, sources are human activities and noise is termed “microtremors.”

Bard et al. noted that the 1-Hz division between microseisms and microtremors is not absolute, as the limit can shift below 1 Hz at sedimentary (vs. hard rock) sites. Tables 1 and 2 present Bard et al.’s synthesis of noise sources and composition, respectively.

Table 1. Synthesis of noise sources according to frequency, after Gutenberg (1958) and Asten (1978) and Asten and Henstridge (1984) studies (Bard et al. 2003, Table 1).

	Gutenberg (1958)	Asten (1978); Asten and Henstridge (1984)
Waves striking the coast	0.05–0.1 Hz	0.5–1.2 Hz
Monsoon/ large-scale metrological perturbations	0.1–0.25 Hz	0.16–0.5 Hz
Cyclones over the ocean	0.3–1 Hz	0.5–3 Hz
Local meteorological conditions	1.4–5 Hz	—
Volcanic tremor	2–10 Hz	—
Urban	1–100 Hz	1.4–30 Hz

Table 2. Synthesis conclusions about the proportion of Rayleigh and Love waves in noise (Bard et al. 2003, Table 3).

	Frequency range	Rayleigh waves (%)	Love waves (%)
Chouet et al. (1998) (volcanic tremor)	> 2 Hz	30 %	70%
Yamamoto (2000)	3–10 Hz	<50 %	>50%
Arai and Tokimatsu (1998)	1–12 Hz	30%	70%
Cornou (2002)	< 1 Hz	60%	40%

Geographic Variation

Two studies provide examples of regional variation in seismic noise within the continental United States.

Wilson et al. (2002) generated noise acceleration power spectral density estimates between 0.01 and ~8.5 Hz from measurements with seismometers at stations along a 951-km network transecting Utah, New Mexico, and Texas. The seismometers were surface mounted in dirt-covered vaults.

At frequencies of 0.01–0.06 Hz, horizontal components of noise differed more from NLNM and borehole noise than did vertical components. This was attributed to the sensitivity of surface-mounted broadband seismometers to local, dynamic tilting caused by thermal- and/or barometric-induced surface displacements. (Borehole noise measurements were available from a site within 55 km of the midpoint of the Utah–Texas network.) Noise levels varied by as much as 15 dB across the network, which was indicative of the local nature of noise at these frequencies and attributed to the influences of surface site conditions such as slope, diurnal shading conditions, soil type, soil moisture, and vault design. At microseismic frequencies (0.06–0.3 Hz), the noise components were indistinguishable from borehole noise. At high frequencies (0.3–8.5 Hz), noise levels were higher than borehole noise and depended on proximity to population centers, transportation corridors, and oil/gas production sites.

Young et al. (1996) measured seismic noise with seismometers at the surface and within boreholes at three sites, and generated spectrograms (maximum frequency ~60 Hz) from data collected over at least one year. At Amarillo, TX, where seismometers were at depths of 5, 100, 200, 367, 1219, and 1951 m, noise levels primarily varied with cultural and wind activity, cultural noise was evident at 1–40 Hz on a 10- to 12-hour daily cycle and exceeded background levels by up to 10 dB, and cultural noise was present at all depths but most evident at 1219 and 1951 m, where wind-induced noise was weaker.

At Datil, NM, where seismometers were at depths of 0, 5, 43, and 85 m, sustained cultural noise was absent, which was attributed to the site's remoteness from populated areas. At Pinedale, WY, where seismometers were at depths of 3, 13, 30, 122, and 305 m, a pattern of progressive daytime increases in wind noise dominated over the diurnal pattern in cultural noise.

Seismic Noise Categories by Source

Road Noise

Road noise is the term applied to ground motion induced by vehicles moving on established travelways. Interest in road noise generally arises from concern about quality of life or damage to structures in the vicinity of high-volume traffic. Road noise depends on road structure, the materials through which the vehicle-induced vibrations propagate between the road and the measurement point, and the propagation distance, as well as traffic density and vehicle type and speed. Despite differences in these factors among the studies summarized below, there is agreement in the frequency range of road noise (Table 3).

Table 3. Frequency content of road noise.

Study	Location	Frequency range (Hz)
Butler (1975)	Georgia, Alabama	2–50
Coward et al. (2003)	Australia	5–30
Holub (1998)	Czech Republic	3–25
Long (1993)	Georgia	1–50
Schofield et al. (2000)	Washington	1–50; 4–12 peak
Lombaert and Degrande (2001)	The Netherlands (test track)	5–40 (speed dependent)

Butler (1975) generated graphs of road noise amplitude vs. frequency (2–50 Hz), at offsets from the roadbed of ~15 to 75 m, for several locations in Georgia and Alabama and for various vehicles. Ground motion spectra of a car traveling at the same speed over the same portion of road at a distance of ~15 m varied with each pass of the car, which Butler attributed to the car going over different road bumps each time. His measurements demonstrated the effect of near-surface geology on ground motion: at ~45 m from the road, high-frequency energy (28–50 Hz) that was evident as spectral peaks at a hard rock site was absent from a clay fill site.

Long (1993) presented an empirical formula for attenuation of seismic road noise based on measurements for steady auto traffic (15–60 cars/min) in the Atlanta, GA vicinity:

$$\text{Log}\,[A\ (\text{mm/s})\} = 0.9 - 1.25 \times \text{Log}[r\ (m)] \qquad (1)$$

where A is the root-mean-square amplitude of particle velocity and r is the distance from the roadbed. Long noted that a single car fits the same rate of decay but with half the amplitude. The equation is valid for 30–300 m. The upper limit is constrained by the "typical background vibration levels found in a suburban environment;" the lower limit was chosen to avoid near-source effects on amplitude measurements within one wavelength of the source.

Overall, the frequency content of the road vibrations measured by Long was 1–50 Hz, with peaks near 15 Hz, at a site with average topography of 1–3 m. Where there was zero relief, the vibration level was a factor of two higher than predicted by equation 1. Where there was ~13 m of vertical relief within 50 m of the roadbed, the lower frequency components of seismic vibration were severely attenuated; the measured particle velocity was 0.002 mm/s (~ background level), with most of the energy in the 40- to 50-Hz range. Generally, where the intervening topography was greater than average (1–3 m), vibration levels decreased at a rate of 3 dB per meter of relief, which Long attributed to surface waves reflecting from the topography.

Coward et al. (2003) were concerned whether road noise would interfere with measurements of gravitational waves at an observatory in Australia. An observatory in Hanford, WA, had reported that local traffic (passenger vehicles to heavy trucks) caused vibrations at 1–50 Hz that peaked at 4–12 Hz (Schofield et al. 2000). Coward et al. recorded ground vibrations at the Australian observatory as a vehicle approached and proceeded past their instrumentation; the vehicle's closest point of approach was 24 m. Road noise was evident in the frequency band 5–30 Hz, compared to vibrations when the vehicle was more than 100 m distant. Rapid fluctuations in road noise were attributed to varying axle loads caused by road unevenness.

Holub (1998) monitored seismic noise at sites throughout the Czech Republic. Road traffic, whether cars, buses, or trucks, generated vibrations at frequencies of ~ 3 to 25 Hz, with variable amplitudes.

Lombaert and Degrande (2001) conducted experimental validation of a model of traffic-induced vibrations developed by Lombaert et al. (2000). Predicted and measured peak particle velocities (PPV) as a function of vehicle speed (30–70 km/h) and distance from the road center line (5–50 m) agreed within a factor of two. Plots of PPV vs. frequency (<50 Hz) showed broadening of strong frequency content with increasing speed at a given distance: 5–20 Hz at 30 km/h (~20 mph), 10–30 Hz at 50 km/h (~30 mph), and 10–40 Hz at 70 km/h (~43 mph).

Train Noise

Train noise is restricted to locations through which railways pass, yet in uninhabited areas it might be the primary source of cultural noise. Two reportings of main-line rail noise are Sanford et al. (1968) and Holub (1998). The former identified train noise at frequencies below 5 Hz at a site near Socorro, NM. The amplitude of ground motion was proportional to the length and speed of the train, but it varied also with local topography, i.e., the greater the topographic relief between the train and measurement point, the smaller the vibrations. Holub cited vibrations in the frequency range 2–10 Hz, with variable amplitudes for moving trains, for rail noise in the Czech Republic.

Manning et al. (1974) proposed a means of predicting mass-transit train noise. From published measurements, they developed a plot of frequency-dependent ground vibration levels at a distance of ~8 m (25 ft) from an at-grade tie-and–ballast track on which a mass transit vehicle was moving at 96 km/hr (60 mph), as well as a plot of the frequency-dependent difference in surface vibration level for propagation distances other than 8 m. The former would be used to estimate frequency-dependent ground vibration levels at 8 m for a speed of interest, using a relationship between vibration level and speed. The latter would then be used to predict vibration levels at other distances from the track.

Ground vibrations induced by trains have been studied to identify track bed constructions and placements that mitigate vibrations. Anderson and Nielsen (2005) modeled a track on a half-space and subjected it to a moving harmonic source in an investigation of construction methods (e.g., trenching, soil stiffening) that alter the propagation of ground vibrations.

Wind Noise

Wind noise refers to vibrations generated by the coupling of wind energy into ground motion. The wind/ground interaction may be through the wind-induced movement of surface objects, such as trees or structures, or directly through turbulent pressures on topographic irregularities. Wind noise has been investigated for its frequency range, the wind speed threshold for it to become evident, and its persistence with depth (Table 4).

Withers et al. (1996) analyzed ground motion for wind noise at a remote site near Datil, NM. The site was noteworthy for its gentle topography and sparse vegetation (which limited the coupling of wind energy into seismic noise) and its isolation from cultural activity. The nearest paved road was more than 12 km away and lightly traveled, the nearest railroad was more than 90 km away, and the nearest ranch road (other than the dead end access track) was 3 km away. Ground motion measurements were made at the surface (actually, inside a box in a 30-cm-deep hole) and at depths of 5, 43, and 85 m. The instrumentation limited the data analysis to a frequency band of 1–60 Hz.

Table 4. Frequency content and wind speed threshold of wind noise.

Study	Location	Measurement depth (m)	Frequency range ** (Hz)	Wind speed threshold (m/s)
Sleefe et al. (1999)	Remote Nevada site	0.5, 1, 2	10–70	N/A*
Withers et al. (1996)	Datil, NM	Surface	1–60	~3
Withers et al. (1996)	Datil, NM	43	1–60	~3.5
Withers et al. (1996)	Datil, NM	85	1–60	~4
Young et al. (1996)	Amarillo, TX; Datil, NM; Pinedale, WY	0-5	1–60	3–4
Young et al. (1996)	Amarillo, TX; Pinedale, WY	>100	1–60	8–9

* Wind speed threshold not determined; 15 m/s wind during noise measurements.

** Instrumentation limited the high frequency end to 60 Hz.

There generally was a good correlation between high wind and high seismic background noise (SBN). No 8-hr workday noise pattern was evident because of the remoteness from cultural activity, but there was a pattern of late afternoon/early evening increase in wind-related seismic noise due to prevailing wind patterns. The threshold for wind noise to affect SBN at the surface was a wind speed of ~3 m/s. Wind noise then was evident over the entire frequency band (1–60 Hz). The wind threshold for affecting SBN at 43 m deep was ~3.5 m/s; at 85 m deep it was ~4 m/s. Power spectral density plots as a function of frequency and wind speed showed a ~20-dB reduction in SBN between the surface and 43 m deep, with little further reduction to 85 m deep.

Young et al. (1996) also analyzed ground motion in the frequency band 1–60 Hz for depth-dependent wind noise. Overall, wind speed thresholds for the presence of wind noise seemed to be 3–4 m/s at depths of 0–5 m and 8–9 m/s at depths below 100 m. At the Amarillo, TX, site, wind noise was broadband (15–60 Hz), with power levels as much as 20 dB above cultural noise at 5 m deep for high wind speeds. At the Datil, NM, site, wind noise was strongly correlated, broadband (1–60 Hz), as much as 30 dB above background, and evident at all depths (0, 5, 43, 85 m). Because wind speed consistently peaked in the afternoon, the noise spectrograms displayed a diurnal pattern, but one due to wind, not cultural activity. At Pinedale, WY, there also was a diurnal trend in wind speed, which caused a similar pattern in wind noise that predominated over any cultural noise pattern. The strong wind correlation was evident at all depths (3, 13, 30, 122, 305 m). The broadband wind noise (1–65 Hz at 3 m, 1–60 Hz at 305 m) was a maximum of 34 dB above background noise at 3 m, decreasing to a maximum of 10 dB above background at 305 m.

The reductions in wind noise evident when instruments are placed in deep boreholes, as documented by Withers et al. and Young et al., are not expediently attainable. Sleefe et al. (1999) present evidence of the effectiveness of relatively shallow burial in mitigating wind noise. They simultaneously collected ground motion data with 10-Hz geophones at three depths (0.5, 1, 2 m) at a remote Nevada site under 15 m/s nominal wind conditions, producing noise power spectral densities from 1-minute recordings. Wind noise was evident at frequencies of 10–70 Hz (maximum frequency analyzed). High-frequency wind noise attenuated with depth more rapidly than lower-frequency wind noise: 10-Hz wind noise had decreased by less than 1 dB at 2 m, while 70-Hz wind noise was 9 dB down at 1 m and ~18 dB down at 2 m, all referenced to the level of wind noise at 0.5 m.

Wilson (1953) identified the wind-related component of seismic noise at a Cambridge, England, site by comparing ground motion data from a geophone near a tree to that from a geophone in a nearby field. Wind-induced tree movement caused ground motion of 3×10^{-5} cm/s in the frequency range 4–100 Hz.

As cited under “General Characteristics,” Kanasewich noted that a value of 10^{-5} cm/s/Hz peak to peak is a good average for seismic noise at continental sites when wind speed is less than ~3 m/s, but that noise can be at least a factor of five greater when wind speed exceeds ~8 m/s.

Two assessments of wind noise relate to its impact on the amplitudes of the horizontal and vertical components of ground motion, as evident in curves of amplitude ratio versus frequency. [See “Characterizing Seismic Site Effects from Seismic Noise” for applications of the horizontal-to-vertical spectral ratio (HVSR) method.] Koller et al. (2004) determined that many parameters relating to measured ground motion caused the amplitude ratio to vary, but that only wind speed affected the frequency at which the ratio curves peaked. Mucciarelli et al. (2005) found that, provided the sensor was sheltered from direct wind (inside a concrete box at 1.5 m depth), wind increased the amplitude of all components of seismic noise (vertical, east–west, north–south) in the band 0.1–10 Hz similarly, such that HVSR was unchanged. This conclusion was valid for wind speeds up to 8 m/s.

Ocean Microseisms

Ocean microseisms are ground vibrations initiated by the wave motion of large bodies of water. Once the wave motion couples with land, the microseisms may propagate hundreds of kilometers inland.

Microseisms cause two characteristic features of seismic noise in the frequency range 0.01–16 Hz (McNamara and Buland 2004). One feature is a single-frequency peak of lower-amplitude, lower-frequency (0.06–0.1 Hz) ground motion that is generated in shallow coastal waters. This interaction occurs as the coupling of vertical pressure variations from water to land or as the impact of surf on the shore. The second feature is a double-frequency peak of higher-amplitude, higher-frequency (0.12–0.25 Hz) ground motion caused by standing waves formed by the superposition of ocean waves of equal period traveling in opposite directions.

Seasonal and Diurnal Variation

McNamara and Buland (2004) presented two examples of seasonal variation in seismic noise in the continental United States. Microseismic noise (~0.12 Hz) increased by ~15–20 dB in power and decreased slightly in frequency during winter months, which was attributed to the increase in intensity of Atlantic and Pacific storms during the fall and winter. Noise at 0.01–0.02 Hz was stronger in the spring and summer, which was attributed to the larger amplitude of daily thermal variations compared to winter months.

In populated areas, where seismic noise is primarily cultural in origin, diurnal noise variations correlate with patterns of activity. Although prior cultural noise measurements are suspect today unless the type and intensity of cultural activity at a site have not changed significantly, two examples of diurnal variation in cultural noise are presented. Wilson (1953), from measurements of seismic noise levels near Cambridge, England, reported that the daytime level was 10–20 times the nighttime level of 1.5×10^{-6} cm/s rms for the frequency range 4–100 Hz. Kanai and Tanaka (1961) measured seismic noise amplitudes in Tokyo over 24 hours; the daytime maximum was 0.4–0.5 μm, while at night the maximum was 0.1–0.2 μm and the nighttime noise spectra shifted to lower frequencies. Kanai and Tanaka represented seismic noise measurements at 30 Japanese sites by the relation:

$$[\text{Amplitude (midnight)}] = 0.3 \times [\text{Amplitude (daytime)}]^{1.5} \qquad (2)$$

for amplitudes in microns. Equation 2 is derived from a plot of midnight vs. daytime amplitudes, "taking into amount [account?] various kinds of subsoil as well as artificial circumstances." By the authors' usage of "midnight" in the text, it appears that equation 2 is more accurately written:

$$[\text{Amplitude (nighttime)}] = 0.3 \times [\text{Amplitude (daytime)}]^{1.5}. \qquad (3)$$

Diurnal variation in seismic noise at remote locations typically is weather related. Wilson et al. (2002) compared median midday and midnight noise levels measured at seismic stations along a ~951-km linear network extending between Utah and Texas. At low frequencies (0.01–0.06 Hz), midday noise levels were ~2 dB higher (vertical components) and more than 7 dB higher (horizontal components). The larger variation in horizontal noise components was attributed to diurnal variations of wind, barometric pressure, and temperature, which interact with vault geometry and/or soil conditions to cause tilting of the slab on which a seismic sensor is mounted. At microseismic frequencies (0.06–0.3 Hz), day/night variations were less than ~1 dB. At high frequencies (0.3–8.5 Hz), the average midday noise levels were as much as 8 dB higher than midnight noise levels.

Characterizing Seismic Site Effects from Seismic Noise

Nakamura (1989) advocated the H/V method, by which the spectral ratio between the horizontal and vertical noise components recorded at a site is analyzed to predict the local response to seismic waves. Curves of H/V amplitude ratio versus frequency show a peak at the site's fundamental frequency. The method is applicable to stratified sites (surface layer overlying a more rigid layer) with cultural or natural seismic noise.

In a systematic investigation of the method to establish its scientific foundation, Koller et al. (2004) evaluated 60 parameters (in the categories of recording parameters, in situ soil/sensor coupling, artificial soil/sensor coupling, sensor setting, nearby structures, weather conditions, noise sources, and stability with time) for their influence on H/V ratio. Although many parameters affected the amplitude ratio, only wind speed also caused variation in the peak frequency. Among the authors' conclusions were recommendations to avoid measurements during strong wind or strong rain and to avoid including transient ground motion generated by nearby machinery, footsteps, or vehicles (moving or idling).

Panou et al. (2005) evaluated the usefulness of the H/V method of site seismic characterization using Thessaloniki, northern Greece, as a test case. There was good correlation between the H/V parameters of fundamental frequency and maximum amplitude ratio, and the site-specific isoseismal intensity curves and damage grades (damage level) for a 1978 earthquake. Their assessment was based on the 0.2–20 Hz frequency range for noise in the downtown city district. Fundamental frequency decreased on a transit from the city interior to the shoreline, which was consistent with increasing thickness of alluvial deposits toward the shore.

3 Seismic Detection of Personnel

Noise Impact

Depending on its magnitude and frequency content, seismic noise can interfere with seismic detection of personnel in two ways. Current seismic sensors trigger on a perturbation to the background level of ground motion. Strong seismic noise can mask a weaker disturbance caused by a moving person, resulting in either non-detection or reduced detection range. With the latter, the source (person) must be closer to the sensor than is customary for the amplitude of the resulting ground motion to exceed the background level. In such cases there is an inherent danger that the change in detection range is not recognized and so, as compensatory measures are not taken, gaps in sensor coverage exist.

Once triggered, some seismic sensors process the sampled ground motion to determine its frequency content as a basis for identifying the source of the detected ground motion as personnel or vehicle. Noise that satisfies discrimination criteria for vehicles may interfere with personnel detection if the sensor is designed to generate a "vehicle alert" whenever the frequency band characteristic of vehicle-induced ground motion is strong. By suppressing any "personnel alert" in favor of reporting vehicle intrusion, which is assumed to be more threatening, the vehicle alerts are nuisance alarms that render the sensor ineffective for detecting personnel intrusions.

Comparison of Seismic Noise and Footstep Signatures

Ground motion was recorded at a rural location in Enfield, NH, using a 4.5-Hz vertical geophone as the seismic transducer. A 250-Hz anti-alias filter was applied to the data. The site was a grass-covered field remote from operating machinery. The nearest vehicle traffic passed intermittently on a gravel town road 225 m distant. A portable weather system sampled wind speed at ~15-s intervals and recorded average, maximum, and minimum wind speeds every minute. Seismic noise was recorded while all on-site personnel and vehicles were stationary. Footstep-induced ground motion was recorded while one or more individuals walked set paths.

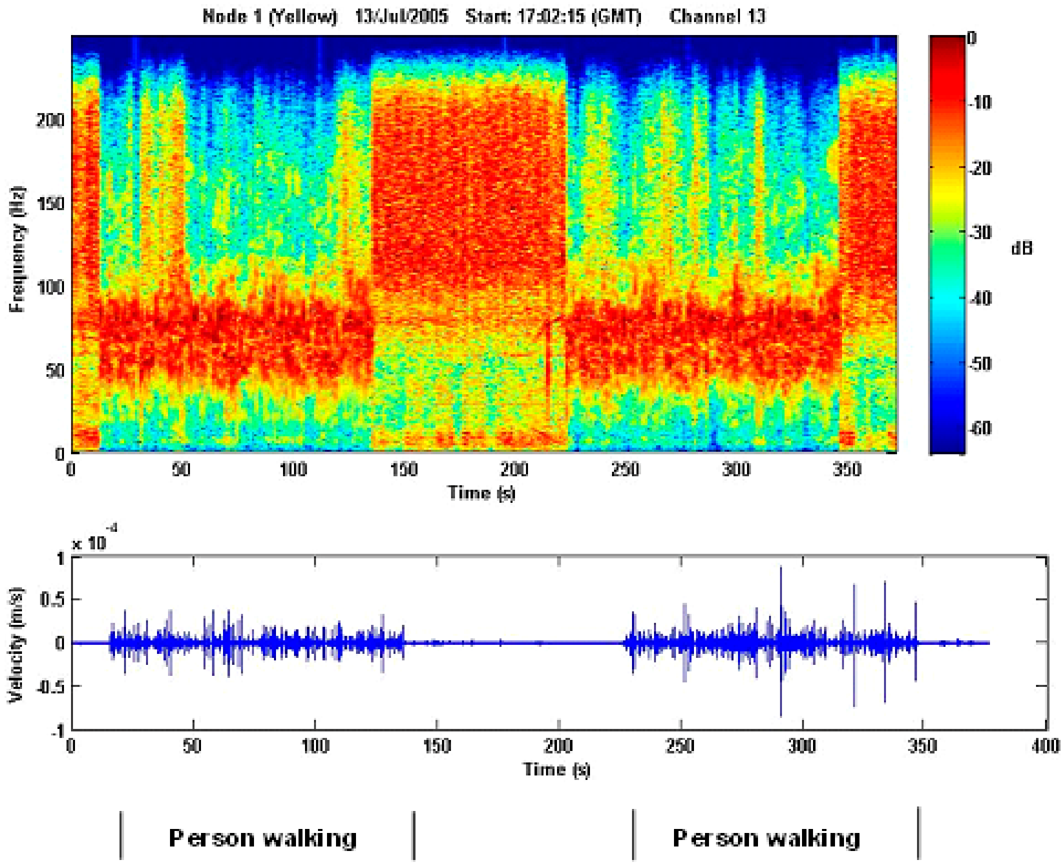

Figure 2. Spectrogram (top) and time series display (bottom) of a 375-s record of vertical ground motion in which segments of seismic noise alternate with segments of footstep-induced ground motion. The spectrogram is normalized at each second to the maximum amplitude over all the frequencies at that time. This causes the apparent maximum energy level to be the same at each time regardless of the walker's activity (moving or stationary).

Figure 2 shows a time series display and spectrogram for a 375-s record of ground motion during alternating periods of noise and footstep activity. The record begins with a 15-s segment of background noise. Next is a 120-s segment of ground motion induced by a single person walking a 10-m-radius circle with the geophone at the center. Then there is a 75-s segment of noise followed by a second 120-s segment of footstep-induced ground motion as the person repeats his walk on the 10-m circle. The final 15 s is noise. The maximum wind speeds during each minute of this record were 1.5–3.9 m/s; the average maximum wind speed was 2.5 m/s. The footstep ground motion is strongest in the frequency range 40–90 Hz, which overlaps wind noise and road noise. Seismic noise is strongest in the frequency range 100–200 Hz. At this rural site during low wind conditions, seismic noise is distinctly different in amplitude and frequency content from the footstep signatures, so it did not interfere with the two commercial seismic sensors in operation at the site, i.e., the seismic sensors successfully detected the walking person. An alternative representation of the same ground motion (Fig. 3) also displays the clear differentiation between noise and footstep-induced ground motion, which is most pronounced in the frequency range 16–100 Hz.

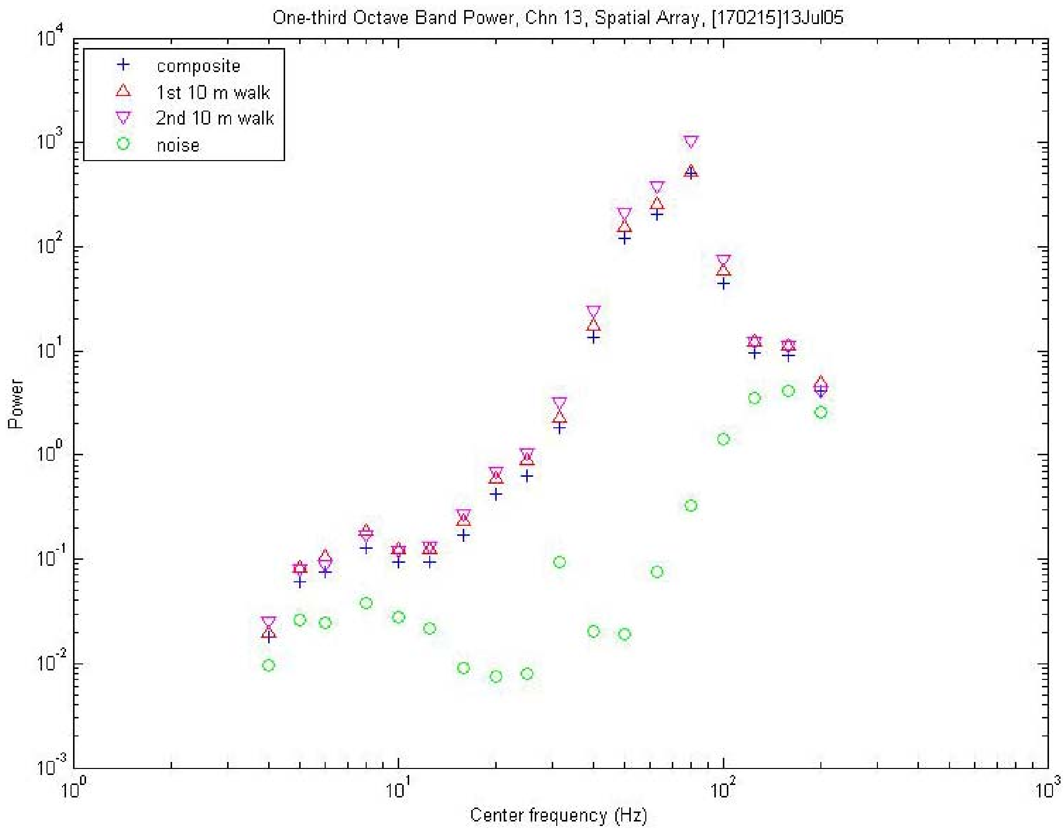

Figure 3. Ground motion power spectra for two 120-s episodes of a person walking a 10-m-radius circle, for a 60-s interval of seismic noise, and for 375 s (composite) of alternating walker events and seismic noise recordings

Based on the wind noise studies summarized above, wind conditions during the Enfield experiment caused barely noticeable wind noise. Under higher wind speeds, the power differential between the walker's signature and wind noise is likely to be reduced. Whether wind noise could ever mask the walker's signature is under investigation.

Ground motion induced by a pickup truck moving at 16 km/hr (10 mph) was recorded on a different day, but with the same geophone in use at the same location as the noise and walker events. The 30-s truck record is shown in Figure 4. The truck crossed the field on a straight path that brought it within 20 m of the geophone. The maximum wind speed during the truck run was 3.2 m/s.

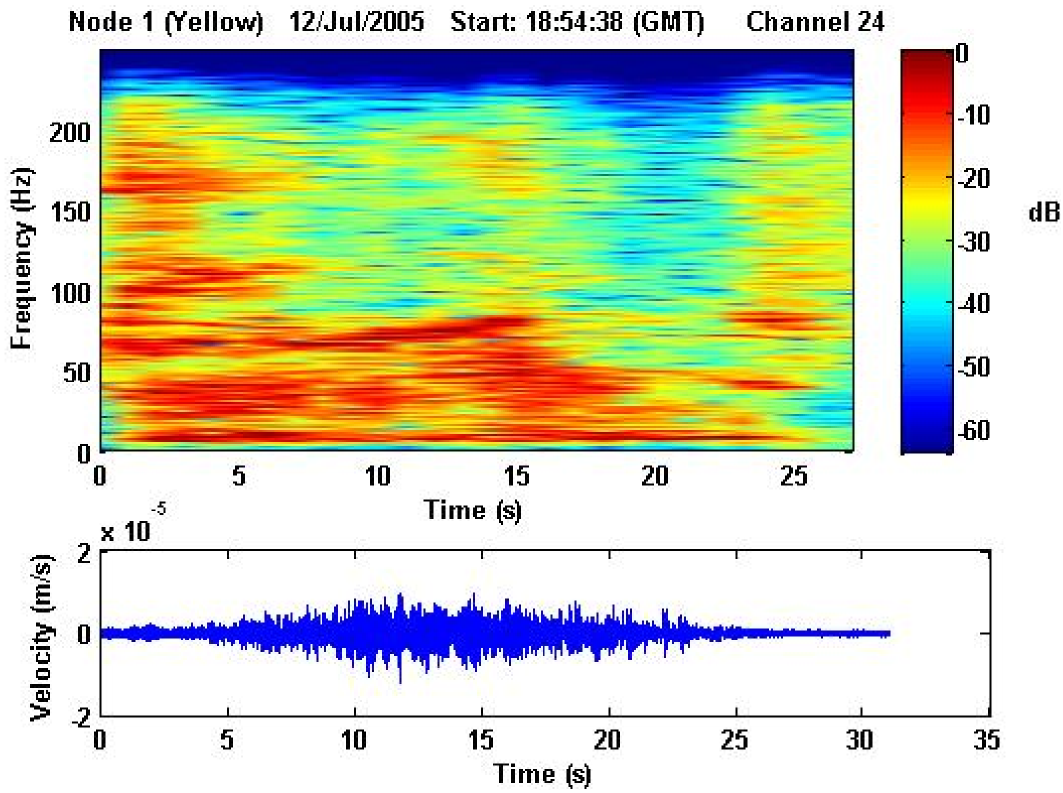

Figure 4. Spectrogram (top) and time series display (bottom) of ~30-s-long record of vertical ground motion induced by a pickup truck moving at 20 mph on a straight path that came within 20 m of the geophone.

The power spectrum of the ground motion induced by the moving truck is shown in Figure 5, together with power spectra of the walking person and noise from Figure 4. The vehicle noise overwhelmed the walking person's signature at all frequencies; the differential is greatest at frequencies of 4 to ~30 Hz.

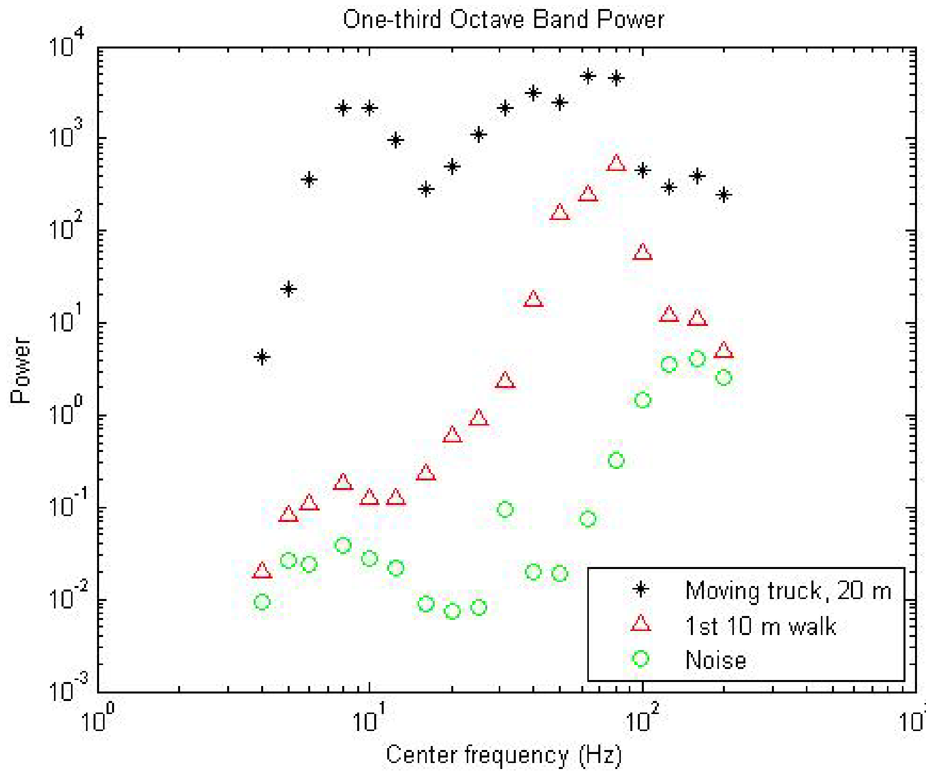

Figure 5. Ground motion power spectra for a pickup truck moving at 16 km/hr, a walking person, and seismic noise during an interval with no personnel or vehicle activity.

4 Conclusions

This review of four categories of seismic noise (road, train, wind, and microseisms) and their variation (seasonal and diurnal) highlights noise characteristics in terms of frequency content and patterns of occurrence. A comparison of road noise and wind noise with a walking person's seismic signature indicates that both, but especially road noise, could interfere with seismic detection of personnel, and it confirms that the frequency content of ground motion is not a sufficient discriminator for personnel detection.

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14. ABSTRACT
Seismic noise refers to the ambient ground motion within which signals of interest are to be detected. Four categories of seismic noise identified by source—road (vehicle), train, wind, and ocean microseisms—are reviewed. Examples are given of the variation in seismic noise by geographic location and by season and time of day, and of a technique to characterize seismic site effects from local seismic noise. Noise impact on seismic detection of personnel is discussed, and ground motion induced by a walking person is compared with noise at a rural site when cultural activity is minimal and when a moving vehicle is present.

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